THE RESOURCES AGENCY OF CALIFORNIA

Department of Water Resources

BULLETIN No. 116-1

CRUSTAL STRAIN AND FAULT MOVEMENT INVESTIGATION

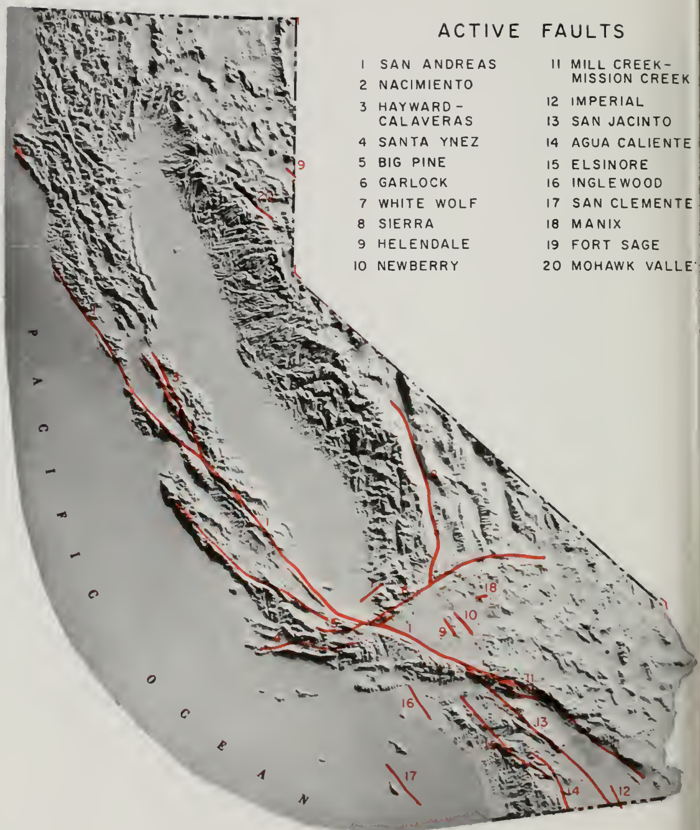
Progress Report

MAY 1963

HUGO FISHER
Administrator
The Resources Agency of California

EDMUND G. BROWN
Governor
State of California

WILLIAM E. WARNE
Director
Department of Water Resources



Active Earthquake Faults in California

State of California
THE RESOURCES AGENCY OF CALIFORNIA
Department of Water Resources

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THE RESOURCES AGENCY OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
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February 27, 1963

The Honorable Edmund G. Brown, Governor, and
Members of the Legislature of the
State of California

Gentlemen:

I have the honor to transmit herewith Bulletin No. 116-1, "Crustal Strain and Fault Movement Investigation -- Progress Report." This investigation was initiated by the department in 1959 under funds budgeted for the California Water Development Program. Plans are under way to implement additional investigations into earthquake problems and their solution based on recommendations of our Consulting Board for Earthquake Analysis.

The major objectives of the department's earthquake engineering investigations are: (1) to investigate, evaluate, and report on all phenomena of earthquakes, faults, and crustal movements which may affect engineering planning, design, construction, operation, and safety of hydraulic structures; and (2) to develop earthquake, crustal movement, and aseismic design factors and criteria to improve or replace the empirical factors in current use for the engineering design of hydraulic structures in California.

Bulletin No. 116-1 has been prepared primarily as a brief report to the Legislature on the objectives, accomplishments, and proposed future program of the Crustal Strain and Fault Movement Investigation -- which may appropriately be referred to as the earthquake hazard studies of the department. This report also briefly refers to the objectives of the programs now being formulated for the department's other earthquake engineering investigations. This report will provide background for a series of earthquake data and earthquake engineering reports which will be issued by the department as progress is made in these investigations.

Sincerely yours,

William E. Warne

Director

STATE OF CALIFORNIA
THE RESOURCES AGENCY OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES

EDMUND G. BROWN, Governor
HUGO FISHER, Administrator, The Resources Agency of California
WILLIAM E. WARNE, Director, Department of Water Resources
ALFRED R. GOLZE', Chief Engineer

DIVISION OF RESOURCES PLANNING

William L. Berry . . . . Division Engineer
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The investigation leading to this
report was conducted under the direction

of

Meyer Kramsky* . . . . Chief, Statewide Investigations Branch

and

Carleton E. Plumb . . . . . . Chief, Planning Investigations Section

by

David M. Hill . . . . Senior Engineering Geologist
William M. Gibson . . . . Associate Engineer, Water Resources

Laurence B. James . . . . Chief Geologist and Coordinator of
Department's Seismic Investigations

*Albert J. Dolcini was Chief of the Statewide Investigations Branch
until July 1, 1962.

ACKNOWLEDGMENT

Valuable assistance, data, and consultation by federal, state, and private agencies and individuals have materially assisted the department in its studies of seismic problems in California. In particular, the continued cooperation and assistance of the following individuals and agencies are acknowledged: Professors Hugo Benioff, Charles Richter, George Housner, and Clarence Allen, California Institute of Technology; Professors Perry Byerly and Donald Tocher, University of California at Berkeley; Dr. Pierre St. Amand, China Lake Naval Ordnance Test Station; the United States Coast and Geodetic Survey; the United States Geological Survey; and the California State Division of Mines and Geology.

Additional guidance in formulating departmental earthquake engineering investigations and in developing rational factors for earthquake-resistant design of hydraulic structures will be provided by the recently constituted Consulting Board for Earthquake Analysis. Dr. Hugo Benioff, Seismologist, California Institute of Technology, specializing in seismic phenomena and instrumentation, is chairman of the board. Members of the board include: Dr. George W. Housner, a Structural Engineer, California Institute of Technology, specializing in engineering seismology and earthquake-resistant design; Dr. Harry B. Seed, Soils Mechanics, University of California at Berkeley, specializing in soil mechanics and model studies in connection with earth dams; Mr. Nate D. Whitman, Jr., Consulting Engineer, specializing in design of hydraulic structures; and Dr. James L. Sherard, Consulting Engineer, specializing in the design of embankment dams.

INTRODUCTION

Bulletin No. 116-1 has been prepared as a brief report to the Legislature on the objectives, present accomplishments, and proposed program of the department's Crustal Strain and Fault Movement Investigation in the Division of Resources Planning. This activity is a part of the department's overall program of earthquake investigations. Specialized technical model and earthquake design studies, which are conducted by the Division of Design and Construction and the Supervision of Dam Safety Office, are only briefly mentioned herein. The data collected by the Crustal Strain Unit are utilized by the Division of Design and Construction in their program for developing earthquake design criteria for the State Water Facilities. These data are also of value to the Supervision of Dam Safety Office, the Division of Operations, and the planning activities of the department.

This bulletin is the first of a series of reports which will present the results of the various technical earthquake and crustal movement studies being conducted in the Division of Resources Planning. The first basic data report in the series will be Bulletin No. 116-2, "Earthquake Epicenters and Faults in California."

The Crustal Strain and Fault Movement Investigation was initiated by the department in January 1959. Funds for the Crustal Strain Program are provided in the 1962-63 budget, page 679, line 8.

CALIFORNIA EARTHQUAKES -- A SPORADIC PROBLEM

The California Water Plan envisions a system of reservoirs, aqueducts, pumping plants, and other hydraulic facilities throughout the State. The potential threat to these structures posed by earthquakes and crustal movements is an important factor in the location, design, construction, and operation of the various facilities of such an extensive project. Inasmuch as precautionary aseismic design measures entail additional expense, any appraisal of earthquake risk must also include consideration of the purpose, type, and useful life of the structure concerned, and the seriousness of the loss or the danger to life should structural failure occur. The Department of Water Resources has undertaken the Crustal Strain and Fault Movement and other earthquake engineering investigations herein described, to provide objective evaluations of the potential hazards related to our sporadic earthquakes, and to provide rational criteria for the design of hydraulc structures to obviate or minimize any adverse effects from future earthquakes.

Evaluation of earthquake activity indicates that California is located in the second most highly seismic area in the United States, the first being Alaska. The great majority of reported earthquakes in California are associated with major fault systems concentrated in the Coast Ranges in Central and Northern California, in the Transverse and Peninsular Ranges in Southern California, and in the Sierra Nevada. Locations of some of the known active faults are shown diagrammatically on the Frontispiece and in Illustrations 1 and 2.

Illustration 1 shows an aerial view southeastward along the San Andreas fault north of San Bernardino near the proposed Devil's Canyon Powerplant No. 2. The earthquake of January 9, 1857, which was comparable in strength to the famous 1906 San Francisco earthquake, accompanied rupture and displacement of the ground along the fault line in the area shown in the picture. The rupture extended northwesterly from San Bernardino about 150 miles or more, following the trace of the fault through Antelope Valley, the mountains south of the San Joaquin Valley, and Carrizo Plain.

Illustration 2 shows an aerial view of the San Andreas fault near Carrizo Plain, which is located about 18 miles west and northwest of Taft and is about 150 miles northwest of the area shown in Illustration 1. The abrupt offsets of stream channels at the fault line provide evidence of recent lateral fault movement. The photo is typical of an area that will be crossed by the California Aqueduct.

Effects of earthquakes which may damage hydraulic structures include: shaking of foundations, surface rupture, earth lurches, slumps, mudflows, landslides, avalanches, seiches, and seismic sea waves. Any one or a combination of these effects, if not properly considered in design, could seriously impair the usefulness of hydraulic structures. Crustal strain in the form of tilting of the land surface occurs along some faults, and could alter the hydraulic gradient of a canal or place a critical pumping plant facility out of alignment without an actual earthquake. Nevertheless, experience has shown that with proper evaluation of these

Illustration 1. San Andreas Fault, San Bernardino County (looking southeast). The San Andreas fault (indicated by arrows) forms the boundary between the San Bernardino mountains on the left and the alluvium-filled valley on the right.

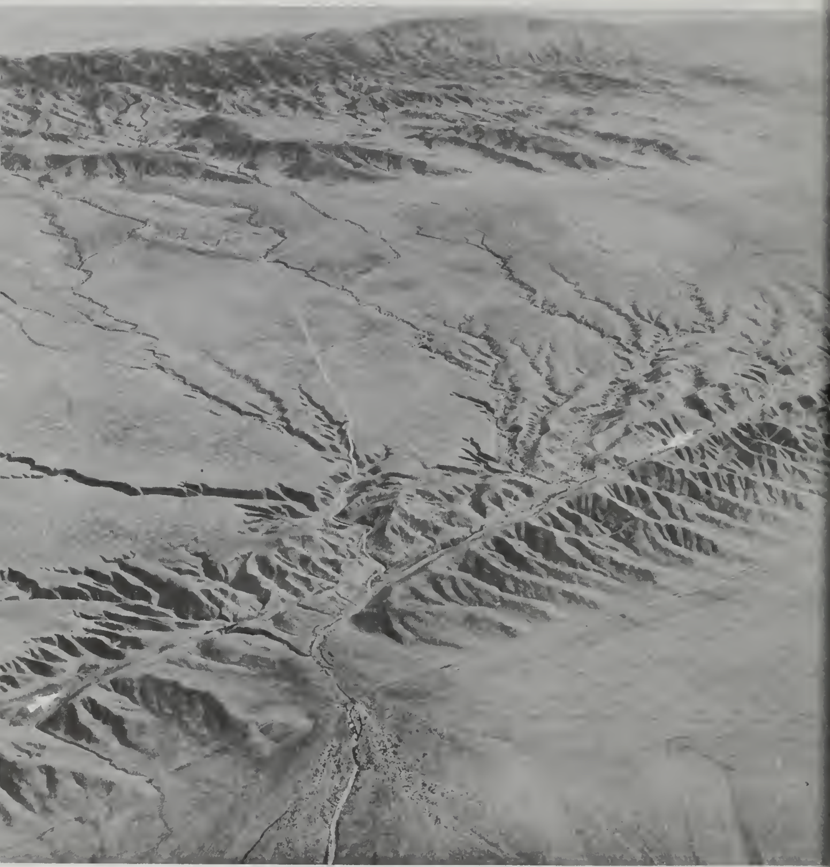


Illustration 2. San Andreas Fault, San Luis Obispo County (looking east across fault). The California Aqueduct will cross the San Andreas fault in areas similar to the road crossing shown in the center of the photograph. The fault is indicated by arrows.

factors incorporated in design of hydraulic structures, these potential problems can be minimized.

Although California is an area of high seismic activity, a preliminary review of available data on hydraulic structures in California indicates that relatively few structures have been damaged by earthquakes during the past 70 years. During this period, 14 earthquakes caused some damage to 10 dams, 3 small water supply reservoirs, 1 sewage treatment plant, 1 pumping plant, and 1 powerplant. For example, in 1940 the All-American Canal was displaced 14 feet 10 inches by movement along the Imperial fault just prior to initial use. Repairs were immediately implemented, and the canal was then placed in operation. During the 1906 San Andreas earthquake, displacements of 5 to 8 feet were measured in fills and outlet tunnels of three earthfill dams in the Crystal Springs area south of San Francisco where they were cut by the San Andreas fault. It should be noted that these dams did not fail. Shaking of the foundation and materials in Sheffield Dam (earthfill) in Santa Barbara County during the 1925 earthquake caused failure of the structure. The dam was rebuilt during the same year.

Reports of earthquake damage to hydraulic and other engineering structures may be unintentionally misleading as to the extent of the damage, because emphasis may be placed on the instances of damage rather than on the number of structures which survive earthquakes unscathed. However, the past record of hydraulic structures damaged by earthquakes is a reminder that damaging earthquakes have occurred repeatedly in the past and can be expected to recur in the

future. Therefore, planning, design, construction, and operation of the State Water Facilities must take into account all phases and ramifications of earthquake phenomena to minimize the potential damage from future earthquakes and to assure the safety of the facilities.

REVIEW OF EARTHQUAKE INVESTIGATIONS IN CALIFORNIA

Even though the historical record of California earthquakes extends back to 1769, it was not until 1887 that systematic compilation and publication of earthquake descriptions were inaugurated. This valuable program was undertaken by the University of California. The first seismographs in California were installed during the late 1880's and early 1890's at the following San Francisco Bay area locations: Lick Observatory on Mt. Hamilton; University of California (Berkeley); Chabot Observatory (Oakland); Mills Seminary (Oakland); and University of the Pacific (San Jose). Lick Observatory began its active work in 1888 and was the early leader in collecting reports of earthquakes on the Pacific Coast.

Following the destructive San Andreas earthquake and fire which devastated San Francisco in 1906, a State Earthquake Investigation Commission was formed to study all aspects of the earthquake and the resultant damage. Funds for operation of the commission and publication of its findings were provided by the Carnegie Institution of Washington, D. C. Soon after the earthquake, the United States Coast and Geodetic Survey remeasured its triangulation net in the area to determine the width of the zone affected by crustal movement.

After publication of the report of the Earthquake Investigation Commission, public "earthquake psychology" developed which opposed discussion or investigation of earthquakes, because it was "bad for business." In the midst of this opposition, a group of

San Francisco Bay area geologists and others organized the Seismological Society of America. Bulletins of that society have been issued quarterly since 1911. Funds to support earthquake investigations in California came from outside the State during those lean years -- largely from the Carnegie Institution of Washington. In 1921 the Carnegie Institution of Washington established a program for earthquake recording and research, with headquarters in Pasadena. The torsion seismometer was developed for this work by J. A. Anderson and H. O. Wood. By the summer of 1927, four seismograph stations had been installed in Southern California.

The damaging offshore submarine earthquake which struck Santa Barbara in 1925 reawakened public interest in earthquake investigations. As a result, new equipment was installed at the Universi of California at Berkeley and at Lick Observatory. New stations wer established at Stanford University and in San Francisco. In 1925, the United States Coast and Geodetic Survey began publishing descrip tive notes of earthquakes which had formerly been published by the United States Weather Bureau and Lick Observatory. Most of the earl earthquake investigations followed the lines of "pure science" because of lack of public interest and funds for applied research.

In 1930, Stanford University and the United States Coast and Geodetic Survey designed and built a large shaking table for model studies. Even though the studies were useful in measuring the effects of earthquakes on structures, the work was hampered by lack of adequate funds, and subsequently was discontinued. About the same time, the United States Coast and Geodetic Survey began making

periodic geodetic measurements along and across the San Andreas fault at a few critical localities with a view to accurately determining the rate and direction of earth movements. Surveys across the fault from Monterey to Pacheco Pass were made in 1930 and continued in 1932 in the area from San Luis Obispo to Lost Hills, and from San Fernando to Bakersfield. Other projects followed in subsequent years and are being repeated at 10-year intervals, supported by federal funds.

In 1932, the United States Coast and Geodetic Survey designed and put into operation a program for the instrumental recording of strong-motion earthquakes. Prior to that time, no appreciable instrumental data had been obtainable near earthquake epicenters because the initial shock always put sensitive seismographs out of order. This important development enabled the recording of earthquake data near the epicenters. The strong-motion seismographs have been placed in strategic locations like "mousetraps" to lie in wait for a strong shock. Unlike other sensitive instruments, these strong-motion instruments are triggered into operation by the initial shock. There are approximately 80 strong-motion seismographs located in the State of California, centered largely in the metropolitan areas.

The California Institute of Technology has administered a seismological program for Southern California since 1937. The University of California at Berkeley administers a similar seismological program for Northern California. The United States Coast and Geodetic Survey has a separate statewide program. There is a free and informal exchange of data between the organizations that includes copies of all seismograph records. As of 1956, the California

Institute of Technology had 16 stations in operation, the University of California had 11 stations, and the United States Coast and Geodetic Survey had one teleseismic station and about 80 strong-motion stations. The universities are currently adding to their networks.

Activities of various organizations engaged in seismologic investigations may be generally summarized as follows:

United States Coast and Geodetic Survey

1. Collection and publication of descriptive information on earthquakes.

2. Compilation of earthquake history.

3. Preparation and distribution of intensity maps of strong earthquakes.

4. Operation of a network of strong-motion instruments located primarily in metropolitan areas and at the sites of United States Bureau of Reclamation dams.

5. Determination of the natural frequency of vibration of buildings and other structures.

6. Location of epicenters of the larger earthquakes.

7. Precise measurements across earthquake faults by means of triangulation, traverse, leveling, and astronomic azimuths.

8. Cooperation with universities and other agencies in earthquake engineering investigations.

California Institute of Technology

1. Operation of a seismological laboratory.

2. Collection and publication of instrumental data on earthquakes in Southern California.

3. Compilation and study of earthquake history.

4. Operation of a network of seismographs.

5. Research in all problems related to earthquakes.

University of California at Berkeley

1. Operation of a seismological laboratory.

2. Collection and publication of instrumental data on earthquakes in Northern California.

3. Compilation and study of earthquake history.

4. Operation of a network of seismographs.

5. Research in all problems relating to earthquakes.

Stanford Research Institute

Instrumental recording of small shocks, determination of epicenters, and other research activities.

Other Universities and Public Agencies

Activities by universities comprise essentially the operation of a few seismographs and cooperation in epicenter and intensity determinations. In addition, the California Department of Public Works, Division of Architecture, in connection with its administration of the Field Act, has spent approximately $200,000 in research on framed structures, and currently budgets as much as $50,000 annually for this purpose. Other countries, notably Japan, have contributed greatly to earthquake engineering research as applied to framed structures.

Earthquake Engineering Research Institute

The United States Coast and Geodetic Survey, in 1947, established an Advisory Committee on Engineering Seismology to assist the survey in its seismological program. In 1949, the committee was incorporated with the title "Earthquake Engineering Research Institute." Its major purpose is to function as an independent institution to promote continuing research in engineering seismology that would lead to greater understanding of destructive earthquakes and to improvement in safety, and in the economical design, construction, and location of structures of all types to resist forces induced by earth motion.

Activities of the institute center largely on sponsoring and/or promoting research and development by the institute and others, mainly in the field of framed structures, to which a considerable amount of research and study has been devoted. To date, little emphasis by EERI has been placed on earthquake problems relating to dams, canals, and other hydraulic structures.

DEPARTMENT CRUSTAL STRAIN AND FAULT MOVEMENT INVESTIGATION

To achieve the most economic location and design of the various proposed State Water Facilities commensurate with safety and with an uninterrupted water supply, the Department of Water Resources has undertaken an investigation into the nature and extent of the potential problems which relate to earthquakes and crustal movements in California. The various technical studies involved in the department's overall program of earthquake engineering investigations have been grouped into two functional categories. The Crustal Strain and Fault Movement Investigation comprises the first group of studies. These largely involve geology, seismology, and geodesy, and are aimed toward obtaining knowledge of the seismic effects to be expected at specific sites or within specified areas. The second group of studies is more closely associated with structural and soils engineering and is intended to develop procedures for aseismic design and operation of hydraulic structures and for the investigation of safety of dams. Studies in the second group are within the responsibilities of the Division of Design and Construction and the Supervision of Dam Safety Office.

The Crustal Strain and Fault Movement Investigation was initiated by the department in January 1959, following its endorsement by Dr. Hugo Benioff, the department's chief seismological consultant.

Scope and Objectives of Investigation

The earthquake data and earthquake hazard studies included in the Crustal Strain and Fault Movement Investigation in the Division

of Resources Planning have the following objectives:

1. To investigate, evaluate, and report on all phenomen of earthquakes, faults, and crustal movements which may affect engineering planning, design, construction, safety, and operation of hydraulic facilities built by the department.

2. To develop rational seismic and crustal movement fac tors which may be utilized in engineering design, based on frequen and intensity of earthquakes, foundation conditions, probable crus displacement, and associated considerations at each site as relate to structural type and seriousness of loss, should structural dama occur.

Intrinsic in the overall objectives are the following specific objectives:

1. To determine the rate, constancy, and magnitude of ground movements (accumulating crustal strain) near sites proposed for hydraulic structures.

2. To locate active faults which may produce destructiv earthquakes or along which the ground surface may rupture as the result of accumulated crustal strain.

3. To estimate the destructive potential of the probabl earthquake forces which should be anticipated at the site of each structure constructed on or near active faults and on foundations which vary in strength and stability.

4. To estimate the amount and direction of displacement across active faults which may occur either abruptly or gradually, and which may sever or otherwise damage tunnels, conduits, or othe

hydraulic structures, or impede the movement of water by altering the hydraulic gradient.

5. To locate areas of active tectonic uplift or subsidence and to estimate the rate at which the resultant crustal tilting will alter the hydraulic gradient of canals and thus change their capacity.

6. To develop and/or acquire and operate special instruments and equipment of various types, which will implement the foregoing. Such instruments are necessary in order to: (a) detect and measure horizontal and vertical movements of the earth's crust; (b) detect and record the crustal vibrations which may precede earthquakes and/or surface rupture; (c) measure and record the effects of earthquakes on foundation materials at sites proposed for State Water Facilities; and (d) measure and record the effects of earthquakes on existing and proposed hydraulic structures.

7. To collect and compile basic data pertaining to earthquakes, including epicentral locations, magnitude, ground vibration frequencies, and earthquake effects on ground surface and on manmade structures.

8. To prepare programs for electronic data machine processing, analysis, and plotting of data which will facilitate the evaluation of earthquake and crustal movement factors.

9. To develop rational ground motion factors and criteria which may be utilized in developing earthquake-resistant design of hydraulic structures.

10. To investigate the characteristics of, and potential for, earthquake-generated seiches in reservoirs and aqueducts.

Program Accomplishments to Date

The following are the principal activities and accomplishments to date of the department's Crustal Strain and Fault Movement Investigation:

Fault and Earthquake Epicenter Map. A fault and earthquake epicenter map of the entire State, the first of its kind, has been prepared and will be published shortly in Bulletin No. 116-2. Epicenters of all earthquakes of Richter Magnitude 4 and above, which have occurred in California and adjacent areas since 1932, are plotted on the map. The map graphically represents the relative seismicity of the various regions of the State during the past 30 years and will greatly assist engineers, particularly those who design hydraulic structures and other types of engineering structures, in appraising the earthquake hazard at various locations. Over 2,000 epicenters are plotted on the map, which shows groupings of epicenters in certain areas, indicating potentially dangerous seismic activity.

The same map shows the most complete delineation ever published of faults throughout the State. The location of over 3,000 faults is shown. The mapped faults represent a compilation of the latest available geologic mapping, published and unpublished, by the Department of Water Resources, the California State Division of Mines and Geology, the United States Geological Survey, by other state and federal agencies, and by other organizations and individuals. The information on fault locations on this map will be invaluable in planning the location of hydraulic and other structures.

The combination fault and epicenter map is expected to serve as a primary reference for applied seismology throughout the State.

Earthquake Hazard Evaluations. Preliminary evaluations of earthquake hazards at many of the sites of proposed hydraulic structures have been completed or are under way. Such studies include: compilation of the earthquake history of the area, plotting of earthquake epicenters in the vicinity, analysis of the magnitude and intensity of each earthquake, and evaluation of site foundation for stability and susceptibility to shaking. Earthquake frequency, intensity, and acceleration factors are estimated for each site to provide design engineers with a basis for aseismic design of hydraulic structures. These studies also include consideration of some of the side effects of earthquakes which can cause damage, such as surface rupture, slumps, landslides, earth or mud flows, seismic sea waves, and waves generated within reservoir areas.

Electronic Data Processing. A new method of tabulating earthquake data has been developed which utilizes electronic data processing equipment. The latitude and longitude, date, time, accuracy of epicenter plot, and magnitude of earthquakes occurring from 1932 through 1960 have been placed on IBM cards. A tabulation of the earthquake data is included in Bulletin No. 116-2.

Until now such data were not available for the entire State in the files of a single agency, but were scattered in the files of various agencies which have collected and analyzed them for specific areas and purposes. It is now possible to obtain and reproduce the

earthquake record of any area accurately and rapidly. Utilization of the data processing machines will permit machine plotting of epicenters on maps and enable the compilation and plotting of accumulative earthquake energy release for any desired area.

Technical Reports. An annotated bibliography on engineering seismology as applied to hydraulic structures and on earthquake damage to hydraulic structures is being prepared. Selected technica reports are summarized in sufficient detail to provide essential dat as well as descriptions of instrumentation and procedures. In addition to providing the results of the investigations and research con ducted by other agencies, such a bibliography will provide a basis for determining which lines of investigation should be pursued further to satisfy the department's requirements in connection with the planning, design, and operation of hydraulic structures.

Geodimeter Survey. Through the use of a geodimeter which may be generally described as the most precise distance-measuring device available, 65 lines crossing nine faults between San Francisc and Indio have been established. The locations of these lines are shown on Plate 1, titled "Crustal Strain and Fault Movement Investigation Geodetic Program." The purpose of these geodetic studies is to measure horizontal movements of the earth's crust due to strain build-up or fault slippage near the location of present and proposed hydraulic structures, to delimit areas or zones thus affected, and to detect strain build-up that may be released by large earthquake-producing fault displacements. The geodimeter lines are remeasured to determine the rate, direction, and constancy of differential hori zontal movements of the crust on opposite sides of the fault.

Emphasis has been on measurements across the San Andreas fault; most of the other faults crossed are related parallel faults. Most of the geodimeter lines have been surveyed three times, representing approximately 2,600 miles of surveying over a period of three years. It should be pointed out that the data accumulated during this brief period are insufficient to warrant positive conclusions. However, a preliminary evaluation of measurements across the San Andreas fault suggests right lateral movement (the west side moving northward relative to the east side) between Hollister and Simmler. The few repeat measurements available between Simmler and the intersection of the San Andreas and Garlock faults suggest left lateral movement. South of the Garlock fault, it has not been possible to establish a consistent pattern of movement. Repetition of the measurements will, of course, be continued to confirm or revise these preliminary evaluations, and to establish more definite directions, amounts, and, possibly, variations of magnitude in the movements.

Triangulation Survey. Through the cooperation of the United States Coast and Geodetic Survey, an extremely precise triangulation network has been established covering the area of the San Andreas, Garlock, White Wolf, and other faults which converge near the extreme southern end of the San Joaquin Valley. The triangulation network is shown on Plate 1. Repetition of the triangulation will be accomplished after the geodimeter measurements, previously described, indicate that sufficient ground movement has taken place to warrant the resurvey.

Federal-State Cooperative Subsidence Leveling Program

The cooperative leveling program for the measurement of deep subsidence has been sponsored by the department for a number c years to obtain precise data on changes in elevation of the land su face in several areas of the State. The current program is directe toward obtaining such data in those areas of the San Joaquin Valley and the Sacramento-San Joaquin Delta which are critical to the desi and operation of the presently authorized State Water Facilities. The program is administered by the Crustal Strain Unit in the Divis of Resources Planning. Funds for the cooperative program are provided in the 1962-63 budget on page 678, line 40.

The principal cause of deep subsidence in the San Joaquin Valley is attributed to withdrawal of ground water. Vertical tectonic movement also is thought to be a contributing factor in land subsidence in some areas such as at the south end of the San Joaqui Valley near the base of Wheeler Ridge. In either case, the potenti adverse effect on aqueduct gradients locally will be the same as th discussed under tectonic movement as measured by tiltmeters. It is critical for the department to know the varying rates of land subsidence along the aqueduct route so that allowances for this factor may be made during design and construction of the facilities to mini mize the adjustments which may become necessary after the facilitie are placed in operation.

Future Program

The department's seismic investigations, as recommended b the Consulting Board for Earthquake Analysis, include continuation

of the foregoing activities of the Crustal Strain and Fault Movement Program and implementation of additional studies employing instrumentation and engineering models. The solution to earthquake engineering problems requires an integrated program of studies in the following fields: applied seismology, geodesy, engineering geology, and aseismic engineering design. These studies comprise the major phases of the department's future investigational programs.

As mentioned earlier, all of the department's present and proposed studies have been grouped into two functional categories. Studies which fall in the first category and which have been assigned to the Crustal Strain and Fault Movement Investigation in the Division of Resources Planning are discussed under the following headings: Applied Seismology Studies, Geodetic Studies, and Engineering Geology Studies. Studies which have been assigned to the second category and which are the responsibility of the Division of Design and Construction and the Supervision of Dam Safety Office, are presented in the next chapter under the heading, Departmental Earthquake Engineering Studies.

Applied Seismology Studies. Studies of the phenomena associated with earthquakes, and the behavior of foundation materials and hydraulic structures during earthquakes, comprise the keystone in establishing aseismic design criteria. The following seismological studies are part of the future program in the Crustal Strain Investigation:

1. Seismological field studies involving various types of seismic instrumentation will be a major effort of the department's

program in securing information on ground motion characteristics. The following field instrumentation program is under way or in the final planning stages:

a. Installation and operation of a series of strong-motion seismograph assemblies including accelerometers and displacement meters, and supporting seismoscopes. These instruments will be established in critical areas throughout the State and maintained for an approximate 10-year period or longer. In the event of a large earthquake, these instruments will provide valuable design data which cannot be secured from the sensitive instruments. In most major earthquakes, sensitive instruments are commonly rendered inoperative.

b. Installation and operation of portable high-sensitivity seismographs for use in determining the ground spectral amplification factor for critical sites and for determining the spectral response characteristics of selected existing dams. Two high-sensitivity seismographs will be acquired and used at individual structure sites. Where such sites are underlain by alluvium or by slightly to moderately compacted

sediments, one seismograph will be located on the proposed site, and a second instrument will be located on rock in the near vicinity of the site. Frequency curves for design use can be compiled by digitizing records from the two seismographs. Maintenance of these instruments at a proposed site during several smaller earthquakes will provide adequate data for design, thus allowing seismographs to be moved to other structure sites.

c. Installation and operation of a fused-quartz strain extensometer at the recently acquired site in Antelope Valley, Los Angeles County, about 14 miles southeast of Gorman. This instrument will provide a record of the accumulation of strain in bedrock in the wedge-shaped crustal block between the San Andreas and Garlock faults. Earthquakes and surface rupture are the predicted effects which will occur when the accumulating strain is suddenly released. It will also record the transient strains induced in bedrock during the passage of earthquake waves.

d. Installation and operation of tripartite tiltmeters to determine the direction and

rate of tilt along the alignment of aqueduct routes and at other critical locations such as pumping plant sites. Tiltmeters will be located in tectonically active areas, and measurements repeated at periodic intervals, in order to evaluate the extent and the magnitude of the problem.

e. Installation and operation of permanent seismograph stations associated with State Water Facilities. A class A seismograph station is presently under construction at Oroville Dam, Butte County. This station will provide a continuous record of earthquake activity in the Oroville and adjacent areas with respect to the dam and appurtenant structures. Data from this station will be useful in establishing seismic design criteria for projects contemplated under the State Water Resources Development System.

f. Installation and operation of the recently acquired variable reluctance transducer seismograph on the San Andreas fault or in an area of the State, such as the North Coastal area, where seismograph records are insufficient or are not available. A sensitive seismograph station at such a site (1) will

monitor some of the local "rock noises" or microtremors generated by nearby active faults which may be the precursor of a major earthquake, (2) will assist in determining epicentral locations of all earthquakes in the area, and (3) will furnish data on ground motion characteristics at the site.

2. Seismological office studies will be undertaken as needed in order to evaluate seismic hazards at proposed structure sites. Studies undertaken may include, but not necessarily be limited to, the following:

a. Continuing collection and processing of basic data on earthquakes, including their effects on ground surface and on manmade structures, and programming the earthquake data for machine analysis. Coordination with universities and the Coast and Geodetic Survey will be continued to obtain all available seismological data pertinent to the program.

b. Development of special types of earthquake data maps in the future at critical structure sites or areas. The preparation of these special maps depicting magnitude, intensity, and acceleration, and the analysis of their correlation and interrelationship

with the phenomena and expression of strain energy release, are steps in the development of rational factors for earthquake-resistant engineering design of State Water Facilities. Some of the special maps which might be compiled include:

(1) Maps depicting epicentral locations of earthquakes below Richter Magnitude 4. These small earthquakes are the result of minor adjustments in the earth's crust. Such earthquakes release a small, but appreciable, portion of the elastic strain energy which accumulates in the earth's crust as the result of crustal movements. Thses small earthquakes also reflect adjustments in the crust which are the consequence of the rapid release of accumulated strain energy during major earthquakes. The pattern which develops by plotting the epicenters of small earthquakes may provide a clue to the mechanism involved in the strain build-up which results in major earthquakes.

(2) Earthquake intensity maps depicting areas in which earthquake damage has been reported or which have been subjected to moderate to intense shaking. Such a map may be useful in developing rapid, qualitative appraisals of the earthquake hazards at sites of proposed facilities of the State Water Resources Development System.

(3) Maps depicting cumulative earthquake energy release. The map would show graphically whether strain energy is being released by numerous minor earthquakes along some faults or segments of faults or by only a few major earthquakes along other faults or fault segments. Thus, the relative seismic activity of a proposed site could be compared with adjacent areas. This map will assist in planning the location and design of hydraulic structures by providing a numerical basis for appraising the earthquake hazard in any area in terms of the rate at which earthquake energy is released.

3. The Consulting Board for Earthquake Analysis has recc mended that the department undertake a study of long-period standir waves (seiches) which may be generated in reservoirs as a result of earthquake activity. The department's studies will encompass analy sis and evaluation of existing seismograph records and the design, installation, and operation of special instrumentation to measure seiches in reservoirs throughout the State. Correlation of the rec ords from the seiche recorders with records from long-period seismo graphs will enable the department to determine the probability of seiche development in each reservoir and whether the seiches genera by a strong earthquake may be in any way destructive. These studie may be a joint effort of the Divisions of Resources Planning and Design and Construction.

Geodetic Studies. The measurement of vertical and horizontal movements of the earth's crust, using geodetic instruments a techniques, is another essential phase of the department's program for investigating and evaluating the problem of accumulating crusta strain. The following studies and activities will be continued as part of the geodetic phase of the Crustal Strain Investigation:

1. The department's program of geodimeter measurements will be repeated along the San Andreas fault. These measurements are being improved by the adaptation of new techniques for obtainin midline atmospheric measurements. It is planned to extend the department's program of geodimeter measurements to other areas of the State where water development facilities are close to other active faults. These measurements will assist in distinguishing

active from inactive faults and will show the various rates at which parts of the earth's crust are undergoing horizontal movements.

2. Coordination of state and federal earthquake engineering survey programs will be continued. Inasmuch as the United States Coast and Geodetic Survey has been given primary responsibility for long-term earthquake triangulation surveys by act of Congress, coordination is necessary to eliminate overlapping and duplication and to lend more specific direction to the federally financed geodetic programs. Federal programs include fault zone triangulation and astronomic azimuths for the measurement of horizontal crustal movements, and precise leveling to detect vertical movements.

3. The cooperative ultraprecise triangulation project of the department and the United States Coast and Geodetic Survey for measurement of horizontal movements in the area of junction and near approach of the San Andreas, Garlock, and White Wolf faults will be repeated when the department's geodimeter measurements indicate sufficient crustal movement to warrant the repetition.

4. The Federal-State Cooperative Leveling Program for Subsidence, administered by the department, is another area of cooperation with the United States Coast and Geodetic Survey. This program provides basic data on subsidence for planning and design engineers in the department, and for other interested agencies. This cooperative program will be continued.

5. The proposed Federal-State Cooperative Seismologic and Geodetic Programs for Earthquake Engineering, with the United States Coast and Geodetic Survey, will provide complete analysis and interpretation of already completed field work of special geodetic repeat

observations in California fault zones, analyses of existing strong-motion seismograph records of California earthquakes, and additional special geodetic repeat observations and analyses in fault zones in the vicinity of proposed State Water Facilities. The survey will continue to operate and maintain the seismograph stations that have been made part of the cooperative program, and will supply personnel and services to install, operate, maintain, and interpret records of several of the seismographic instruments and stations recommended by the Consulting Board for Earthquake Analysis. This cooperative program does not duplicate the department's Crustal Strain Program, but is an essential complement thereto.

Engineering Geology Studies. Geologic studies are an essential phase of any thorough study of the hazards of earthquakes an crustal movements to manmade structures. Engineering geologists hav a public responsibility to ensure that engineers, architects, proper owners, and public officials are properly informed with respect to earthquake hazards, without being too reassuring or needlessly alarm ing. A clear idea must be formed of the long-term nature of earthquake risk, as well as its relation to the location of faults and to the character of the ground or foundation. The following activities and studies are included in the geologic phase of the Crustal Strain Investigation:

1. Detailed seismic microregionalization maps may be developed for specific sites and/or critical areas. This will entail compilation of the following types of data:

a. Detailed information on potential activity of faults with particular emphasis on those

faults which may affect existing and proposed hydraulic structures.

b. Characteristics of foundation rocks and materials relative to seismic stability.

These data and seismic microregionalization maps are important in any earthquake engineering study, and will be most useful in appraising the earthquake and crustal movement hazards at sites of proposed facilities of the State Water Resources Development System.

2. Geologic interpretation will be provided for the strain build-up detected by the geodetic and geophysical measurements being made in other phases of the investigation.

3. Geologic field studies will include reconnaissance of possible sites for future geodimeter or other geodetic stations, or for future installations of geophysical instrumentation such as seismographs, quartz-strain extensometers, recording tiltmeters, accelerograph, and related types of instrumentation recommended by the department's Consulting Board for Earthquake Analysis.

4. Sites chosen for water development facilities throughout the State will be inspected as part of the department's earthquake hazard evaluation studies, and a geologic evaluation of the earthquake and/or crustal movement hazards will be made at such sites.

DEPARTMENT EARTHQUAKE ENGINEERING INVESTIGATIONS

The primary function of the earthquake engineering studies to be conducted by the Division of Design and Construction and the Supervision of Dam Safety Office will be the development of procedures and criteria for aseismic design of features of the California Water Resources Development System and for investigation of dams under jurisdiction of the department's Supervision of Dam Safety Office from the seismic standpoint. These studies will utilize the aforementioned earthquake hazard studies to obtain an appreciation of the earthquake hazards which should be anticipated in any given area.

The Division of Design and Construction has completed a proof test of the Oroville embankment design. This seismic model study was one of several essential engineering studies which have been completed in connection with the design of Oroville Dam. This proof test of the embankment design was conducted on the shaking table of the Engineering Materials Laboratory on the Berkeley campus of the University of California. The report on this seismic model study will soon be completed

In its report of November 19, 1962, the Consulting Board for Earthquake Analysis recommended that the department undertake the following earthquake engineering investigations in addition to the basic studies previously discussed:

"1. Experimental investigations of the strength and deformation characteristics of soils under simulated earthquake loading conditions for the purpose of determining the appropriate soil properties for use in analyses of earthquake response characteristics. Studies should include:

"(a) Investigations of the strength and deformation characteristics of soils under combined static and pulsating loads.

"(b) Investigations of volume changes and strength characteristics of saturated granular materials under combined shear and vibratory loading conditions and also under high confining pressure conditions associated with large dams with the object of determining the pore pressures likely to develop in embankments composed of saturated granular materials during earthquakes. These studies should be supplemented by investigations of volume changes induced in dry granular materials by typical earthquake ground motions with the object of throwing some light on the extent of subsidence of such soils as a result of earthquakes.

"2. Investigation of methods for predicting the danger of liquefaction of soils both in the laboratory and in the field. This investigation is closely related to that suggested in 1 (b) above.

"3. Investigation of the stability and deformation of model dams during simulated earthquake motions induced by a shaking table. Such studies would serve two purposes.

"(a) As an interim procedure, tests on models of proposed prototypes would provide a guide to the probable effect of earthquakes on these structures. However, this would only be possible for certain types of embankments.

"(b) The results would provide data for determining the applicability of analyses and measured soil characteristics for predicting the response of embankments and dams to known ground motions. Without such tests it is difficult to see how analytical procedures can ever be checked under controlled conditions.

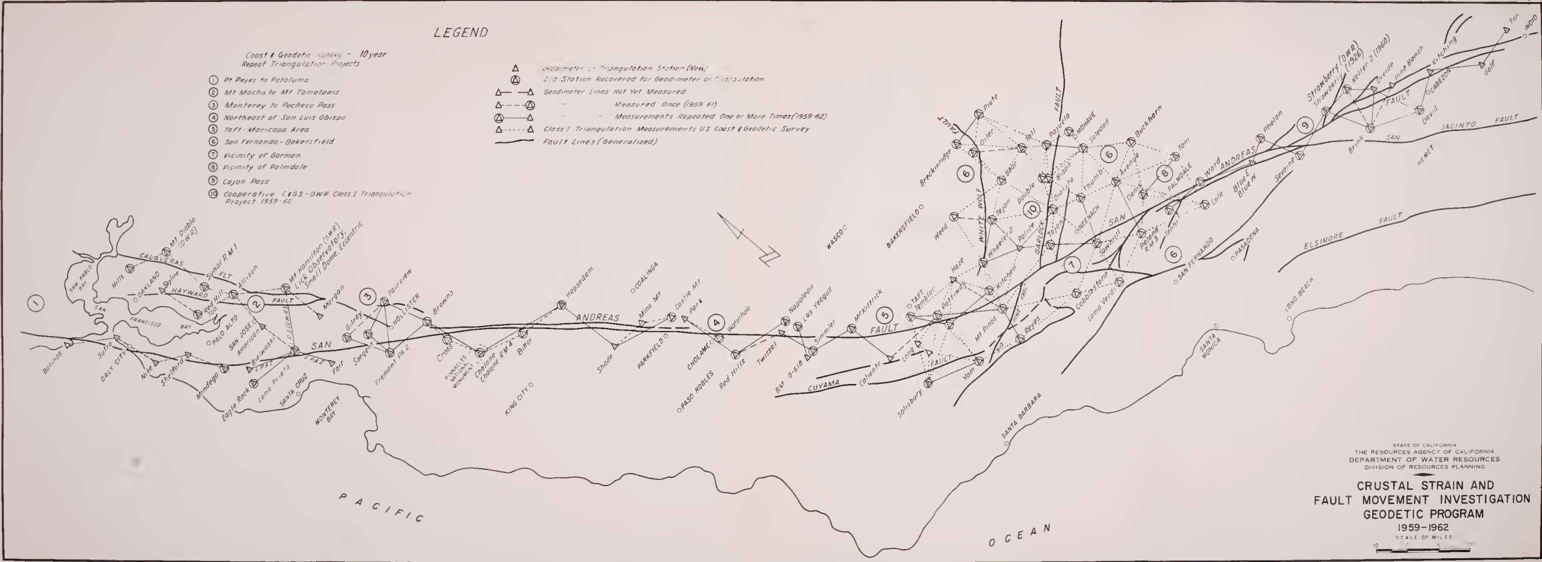
"4. Investigation of the stability against surface sliding of banks of granular materials subjected to earthquake ground motions, for the purpose of checking the applicability of available analyses for computing the acceleration at which sliding is likely to occur and

for determining the extent of sliding and flattening of slopes resulting from a given ground motion.

"5. Investigations of the dynamic behavior of dams by the methods of analytical mechanics. Analyses of the elastic response of dams and embankments have been developed, but studies of elastic-plastic response are required to determine the stresses and displacements resulting from known earthquake ground motions. It is the inelastic displacements which are of primary importance in stability analyses.

"6. Investigations of the dynamic behavior of existing dams by means of field tests using a shaking machine. The results of such studies can be interpreted to evaluate the dynamic shear modulus of the soil comprising the dam and can thus be used to check the validity of laboratory methods for determining the dynamic shear modulus of the soils in advance of construction."

The Crustal Strain and Fault Movement Investigation and the other earthquake engineering investigations herein briefly described, have been undertaken by the Department of Water Resources to provide objective evaluations of possible hazards at hydraulic structure sites as related to the potential effects of California's sporadic earthquakes and to develop rational criteria for aseismic design of structures at those sites to obviate or minimize the adverse effects of future earthquakes. Utilization of the data on earthquake hazards and the criteria for aseismic design will contribute to the competent design of safe and economical hydraulic structures in all areas of the State.



STATE OF CALIFORNIA
THE RESOURCES AGENCY OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

CRUSTAL STRAIN AND FAULT MOVEMENT INVESTIGATION GEODETIC PROGRAM

1959-1962

SCALE OF MILES